Numbers to Keep in Mind

- ~ 4 minutes = daily difference between solar and sidereal time
- ~ 50″/year = rate of precession
- ~ 10″/year = largest stellar proper motion
- ~ 8.3 minutes = light travel time to the Sun
- ~ 30 km/s = orbital speed of the Earth about the Sun

Astronomical Time

There are many definitions of astronomical time (see Eastman et al. 2010, PASP, 122, 935). Here are the two that are ubiquitous:

- **Universal Time** (UT): Local Standard Time in Greenwich, England. (Actually, the definition is a lot more complicated than that, but this is how to think about it.) The **Local Mean Time** is UT minus the longitude (in hours).
- **Local Sidereal Time** (LST): The right ascension that is currently crossing your meridian. (Again, the true definition is more complicated, but this is the basic definition.) Hence

$$\mathbf{HA = LST - \alpha}$$

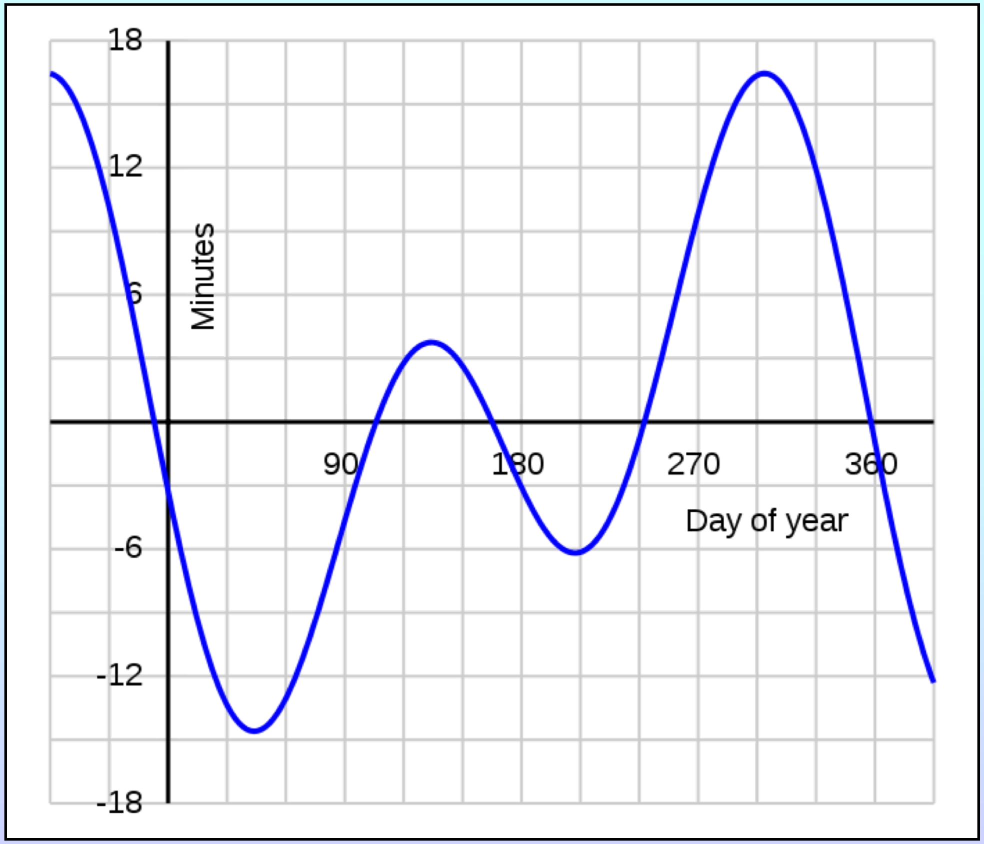
- Because we set our clocks by the Sun (so that local apparent noon is the time that the sun crosses the meridian each day), a sidereal day is 1.00273791 times shorter than a solar day. So each night, a star will transit about 3^{m} 56.55^{s} earlier than the previous night. This adds up to about 2 hours per month.

Apparent versus Mean Time

Note that because the Earth's orbit about the Sun is elliptical, and its axis is inclined 23.5° to the ecliptic, there is a difference between the *apparent* solar time, which defines the hour angle of the Sun, and the *mean* solar time, that is set by steady clocks. The differences are tabulated (daily) in the Astronomical Almanac.

Sundials will be off by up to ~ 15 min, with the difference predictable by a couple of sine waves.

The difference is known as the "equation of time".



Astronomical Years

Astronomers keep track of time (in years) using several different measures:

- **Julian Years:** 365.25 days, with each day having 86,400 seconds. When people say "year" in astronomy, this is what they're usually talking about.
- **Tropical Year:** $365.24219879 - 0.00000614\ T_E$ days, where T_E is the number of Julian centuries since noon on 1900 Jan 0. This is the time between vernal equinoxes and sets our calendar.
- **Besselian Year**: Similar to the Tropical year, though it starts when the apparent location of the Sun crosses ecliptic longitude 280° (which is close to Jan 1). Now obsolete.
- **Julian Date:** the number of days that have elapsed since *noon* on January 1, 4713 B.C. (which means that at noon on Jan 1, 1950, the Julian Day was 2,433,282.0). Occasionally, for computer's sake, you will see time quoted as the Modified Julian Date (MJD). This is the Julian Date minus 2,400,000.5.

Modifications to Astronomical Time

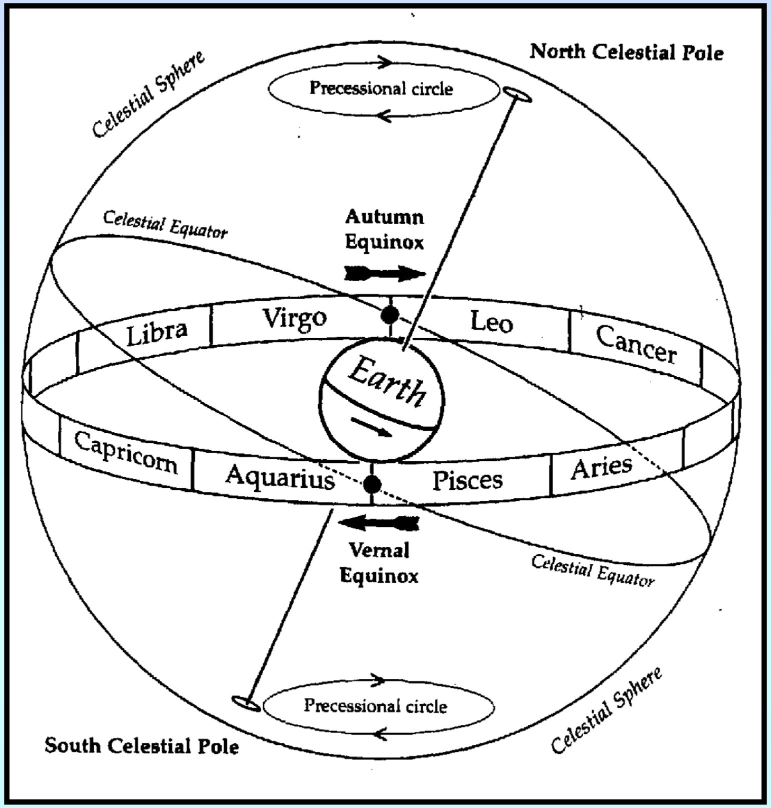
When timing astronomical phenomena, a few additional factors may have to be taken into account:

- **Heliocentric Correction**: because the Earth orbits the Sun, the light-travel time from an astronomical object may vary by up to ± 8.3 min. This is the heliocentric time correction (sometimes called the Rømer delay). (Note: there is also a heliocentric velocity correction, due to the Earth's motion about the Sun.) Time is often quoted using HJD, i.e., Heliocentric Julian Date.
- **Barycentric Correction:** The Sun's reflex motion due to the gravitational pull of Jupiter and Saturn, and the Earth's reflex motion due to the Moon, may change the arrival time of a signal by ± 8 sec. Hence BJD is now preferred over HJD. (The same is true for velocity corrections.)
- **Barycentric Dynamical Correction:** Signals propagating through a gravitational potential are subject to an Einstein delay (time dilation) and a Shapiro delay (curved space paths). For the solar system, these are of the order of a couple of millisec.

Precession

The Earth's flattening and the obliquity of the ecliptic cause the direction of the Earth's axis to wobble on 2 timescales:

- **Precession** causes the Earth's axis to trace a 23.5° circle on the sky every ~26,000 years. The motion is ~ 50.3" per year east-to-west along the ecliptic (opposite the direction of the Earth's rotation and revolution). To first order, an object's coordinates will shift by



$\Delta\lambda = 50.29$ arcseconds/year with $\Delta\beta = 0$

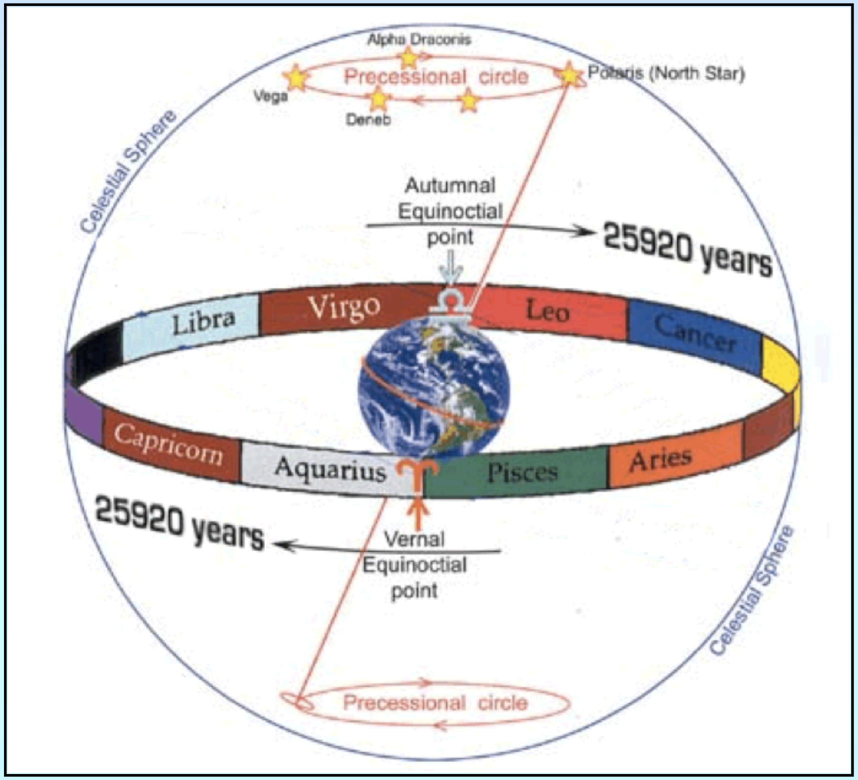
or, in equatorial coordinates,

$\Delta\alpha = [3.07234 + 1.3365 \sin\alpha \tan\delta]$ seconds of time/year

$\Delta\delta = [20.0468 \cos\alpha]$ arcseconds/year

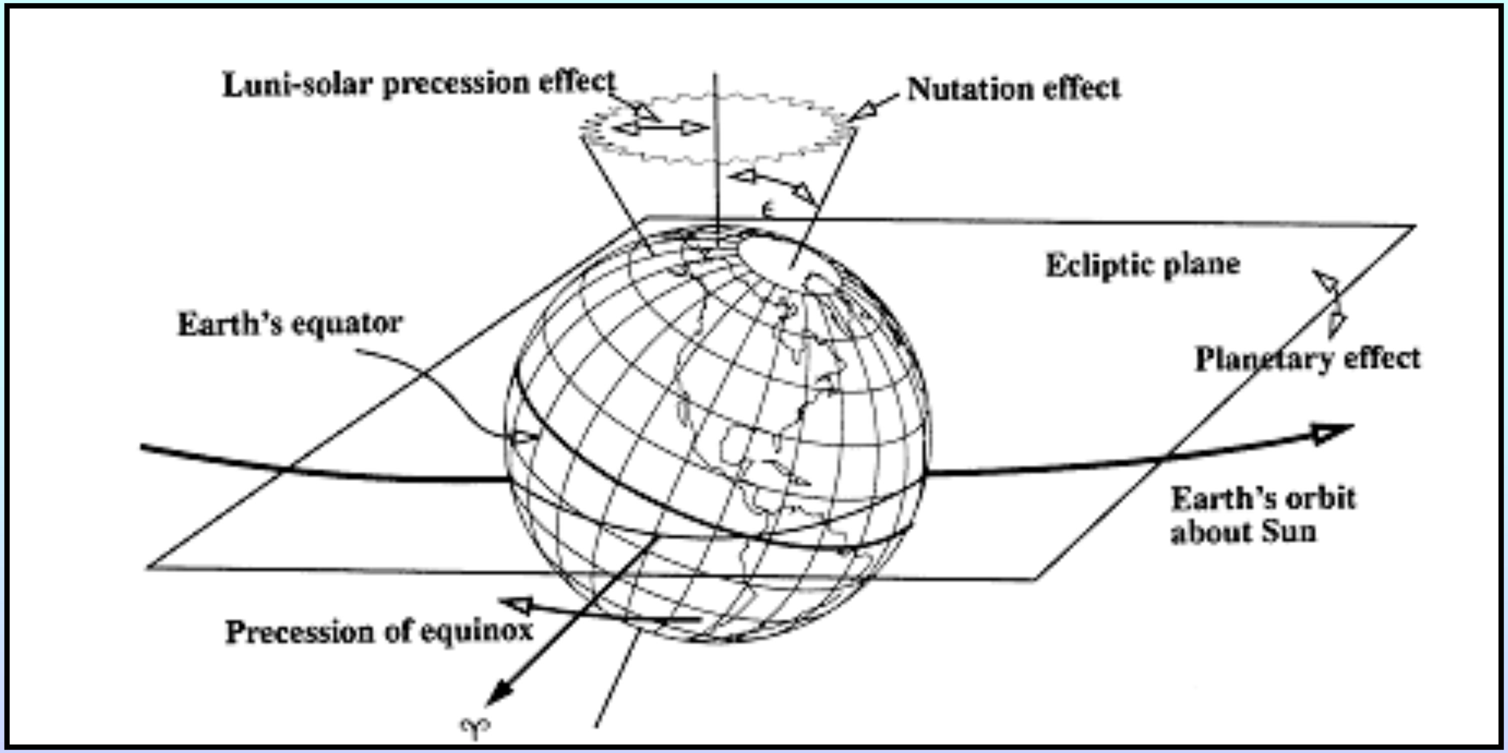
Precession

Note the vernal equinox is sometimes called the "first point of Aries". But the equinox is no longer in Aries – it's a full constellation off.



Nutation

The second timescale for motion of the Earth's axis is due to **nutation.** This correction to precession compensates for second-order torques by the Sun, the Moon, and other planets. The principle term is due to the Moon, whose orbital plane precesses on a timescale of 18.6 years. The amplitude of nutation (i.e., the constant of nutation) is $N = 9.210''$.



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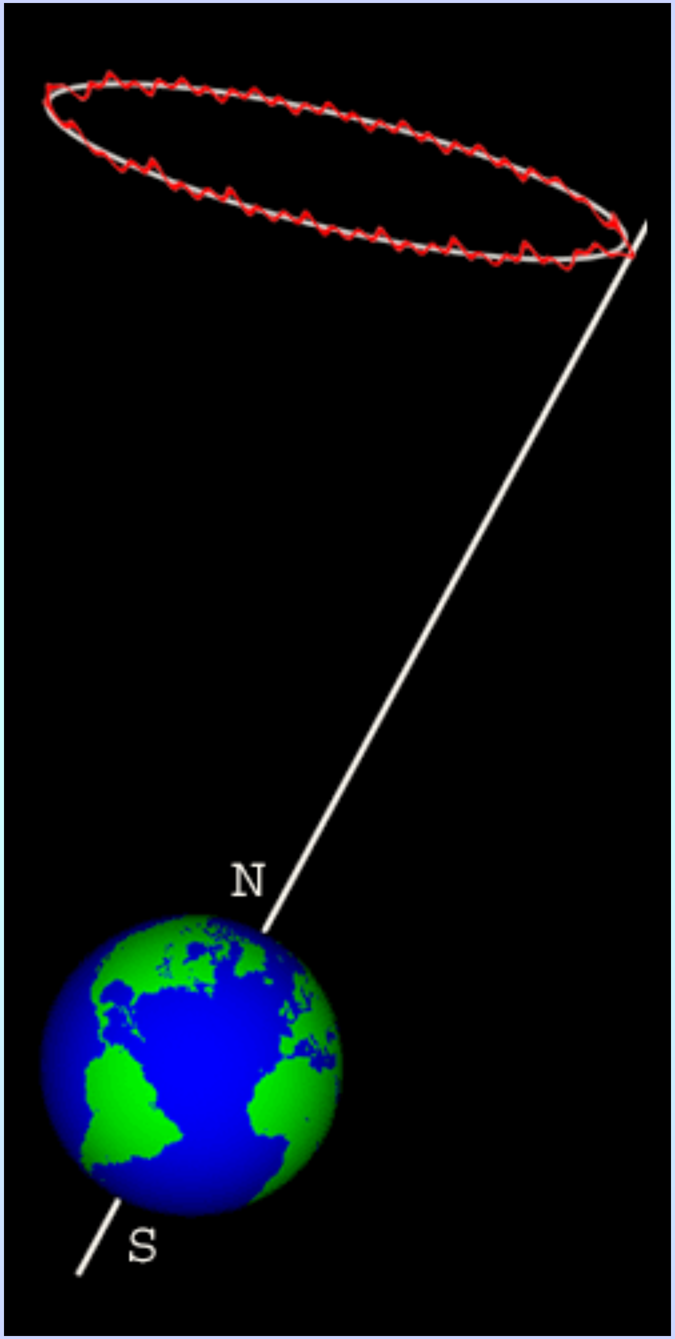
Nutation

Nutation changes the Earth's obliquity to the ecliptic by up to ~ 9" on an 18.6 year timescale. The next strongest period (0.5 years) has an amplitude of ~1.3".

The exact direction of the Earth's pole (as well as positions the Sun, Moon, and planets) can be found in the Astronomical Almanac.



Equinox and Epoch

Because of the effects of precession and nutation, one must *always* include the equinox when quoting coordinates. These days, one usually gives right ascension and declination in J2000 coordinates (though in older papers, you'll often see B1950 quoted).

Note: many times you'll see the *equinox* of an observation referred to as the *epoch* of an observation. Technically, they are different: equinox refers to the coordinate system; epoch states when a star was in a particular place. (Proper motion will cause stars to move on the sky. Therefore, when quoting stellar positions, you must also give the epoch.)

Motion of the Earth

There are several components to the Earth's motion:

Diurnal motion: ~ 74 cos φ meters/sec

- Direction depends on date and time
- Amplitude depends on *geocentric* latitude
- Orbital motion: ~ 29.78 km/sec
- Direction depends on date
- Amplitude depends on date through orbit eccentricity

Barycentric motion: ~ 12.5 meters/sec

- Direction depends on date
- Amplitude depends on date through lunar eccentricity

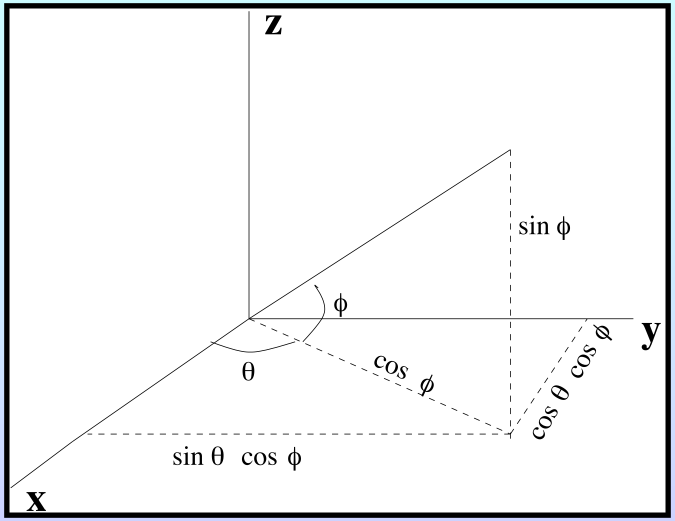
Solar motion: 371 km/s towards $\ell = 264.14^\circ$, $b = 48.26^\circ$

- ~ 15 km/s towards ~ $\ell = 51^\circ$, $b = 23^\circ$ (nearby stars)
- ~ 220 km/s towards $\ell = 87.8^\circ$, $b = 1.7^\circ$ (Galactocentric)
- ~ 316 km/s towards $\ell = 93^\circ$, $b = -4^\circ$ (Local Group)

Correction for the Earth's Motion

To correct velocity measurements for the Earth/Solar motion:

- Determine position of Sun and Moon from Astronomical Almanac or Earth/Moon orbital elements
- Convert apex of motion from spherical coordinates to Cartesian coordinates. [The Almanac does this and gives $(\dot{X}, \dot{Y}, \dot{Z})$.]
- Convert object's spherical coordinates into unit vector Cartesian coordinates
- Dot-product of the two vectors yields projected velocity



$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos\theta\cos\phi \\ \sin\theta\cos\phi \\ \sin\phi \end{pmatrix}$$